Improvements in Pilot/Aircraft-Integration by Advanced Contact Analog Displays

by

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Abstract

Several expert statements selected from literature and concerning the qualities of modern information displays lead to the definition of a number of requirements which should be covered by the displays of the future.

It is shown that abstract displays principally cannot fulfill all these demands and that simply superimposing abstract symbols with the natural view of the outside world or with its artificial equivalent will not result in an optimum solution.

On the other hand, the natural visual contact information has some short-comings too, some of which are identified.

All requirements can be, or will have the best chance to be, fulfilled by pictorial displays which contain the image of real outside world elements, as far as they are useful for information, and of their imaginary extensions into the airspace. The Channel Display is designed according to these rules.

Some test results are shown for confirmation of the concept; special and general problems are touched.

Content

Preface

Our activities, as far as reported here, are primarily viewed from the standpoint of economic increase of Flight Safety. Not only because this is an officially delegated duty of our group but because it should be wise to base the orientation of each research effort more and more on fundamental human needs.

Flight Safety belongs to these.

It seems to be generally accepted that - due to the high contribution in aircraft accidents believed to be human errors - the main branches of the manyfold roots of Flight Safety are found in the area of human engineering.

On the other hand, the general title 'Flight Safety' is closely related, for instance, to many aspects of economy as well. Thus neither the various complex problem areas nor their more or less complicated details can be separated without raising the probability for deterioration of the quality of the progress, for example, in Flight Safety Research.

Since it is a natural human tendency to concentrate on detail and to disregard the whole, every effort should be supported which tends to correlate detail knowledge with the intention of improving the chance to s e e weak points as well as desirable trends, and to respect them.

In other words, problem definition of today should be "system-oriented" - and we see that this is very well known in the USA.

There is another general point of view related to the more or less specific content of this paper:

The efforts to correlate details within the whole are necessary as a preparation of sound decisions for the future. Lack in overall view tends to produce only small steps towards progress, even when a big step is required. Decisions must be made much more "cautiously" than desirable, and their quality does not necessarily rise with the degree of caution, or more precisely: of hesitation.

The complexity of the overall problem requires thinking and speaking about details which belong to very different disciplines of science. Thus, experts in very different fields should closely cooperate in order to evaluate the possible fruitful relations between those; but, we know how difficult it is to achieve this.

A provisionary, but possibly very useful, substitute for direct cooperation is an evaluation of experts' knowledge already available in literature. In many cases sufficient, assured detail 'know-how' is already available for synthesizing a new concept.

Thus, as indicated in the abstract, relatively numerous statements selected from literature are used in order to point out relevant characteristics of the "state of the art", some of it's shortcomings and the main desires for progress. Secondary reasons for making use of these are twofold:

- Many of the facts they describe can not be said in s h o r t more precisely,
- it is only fair to revive again thoughts others expressed before but which are buried in the avalanche of later papers.

But argumentation with literature extracts is sometimes - if it proves to be unconventional and thus inconvenient - tried to be neutralized by the comment: *"... separated from the context."*
Although there can be a risk of modifying the meaning of an original text this does not necessarily imply falsification. An extract describing a complete notion will not falsify, and drawing conclusions from it which had not been drawn by the originator should not effect a distortion. Last not least, recognizing the risk is an important presupposition for discriminating cases of wrong interpretations from evasive comments.

In research on aircraft displays, their valuation is often exclusively concentrated on measurement and statistical processing of parameters concerning 1. guidance precision and 2. workload. A general aspect of this paper will be to demonstrate that these topics are very important, but nevertheless can be presuppositions only for further deciding proof for suitability in the future. This suggests, too, that the two quality measures are insufficient and new additional valuation criteria and methods are needed.

Introduction

Fig. 1 shows possibilities for research and improvement reduced to six ways along which, in principle, the problems of Flight Safety as far as influenced by All Weather Operations can be and are attacked.

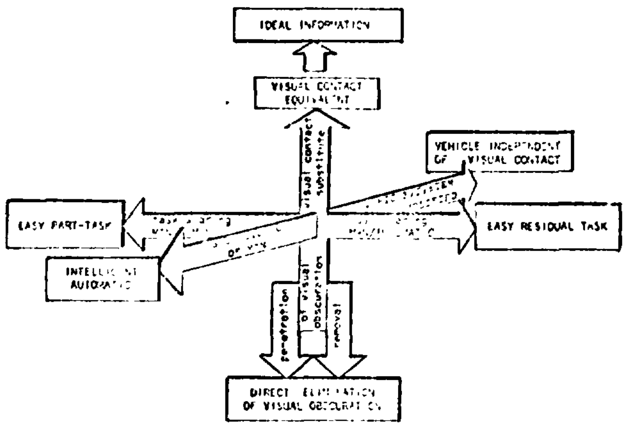

Fig. 1: Possible Ways to Attack the Critical All Weather Flight Problem.

The fundamental reason for the unsolved problems of the critical phases of All Weather Flight is the more or less impaired visual contact to the out-side world [1]. Therefore, trials which intend to disperse or penetrate the obscuration or which offer an artificial substitute for the visual contact are considered, as far as they are successful, to be real s o l u t i o n s in the strict sense. These ways are indicated in the vertical axis of Fig. 1, and they include, in principle, all types of visual information display.

All other ways try to e l u d e the problem by reducing the difficulty level of the critical task or by providing technical means which are independent of visual information. *)

Today all the different ways are used in aeronautics to a more or less high degree. It can be shown, however, that a sound overall solution which is to remarkably raise the safety level needs much better visual contact substitutes than are available today.

Insofar, the paper primarily deals with display and mental processing of information.

*) Details of the different ways are evaluated in a separate paper [2].

On the evolution of the problem to be solved

When improvements are proposed, their valuation can be facilitated if the things to be improved are specifically processed for comparison. Although you are well familiar with the 'state of the art', a very condensed abstraction of it may be allowed here (Fig. 2).

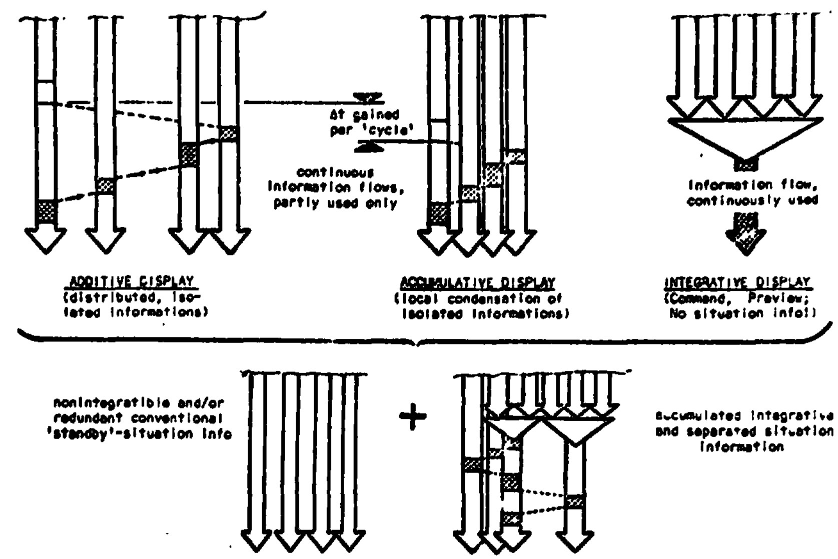

Fig. 2 Main Steps in Evolution of Information Gathering from Conventional Displays.

The ADDITIVE Display which consists of a number of isolated indicators, the number of which increased with time and progress, emerged from the growing importance of limitations of the natural visual contact. The 'single channelness" of the human brain [3, 1] requires that the favourable

continuity of the different information flows be broken by intermittent information scanning. Thus, the precentage of the actually used part of the several continuous information flows decreased during display evolution due to the process of extension and completion - certainly an undesirable trend.

You know that one action against this problem was the local condensation of some indicators in the "combined" or, as it is called here, the "ACCUMULATIVE Display". The advantage: There is some gain in the time needed per - simplified - scanning cycle which in truth has multiloop character.

One of the most important advances in aircraft control was obtained with the introduction of command signals necessary for automatic control and useful for manual control if displayed for instance, with a 'Flight Director'. These types of instruments are collected here, together with others, under the group "INTEGRATIVE Displays".

This information is - under certain presuppositions - a dynamically correct combination of a set of variables which is - on a first view - completely sufficient for the "precision control"-part of the task. With it, the human controller could, in principle, concentrate as the autopilot does on one single control signal per axis. The result, in general, is a more or less remarkable improvement in regularity of guidance precision combined with a reduction in the pilot's mental load under the more or less critical environmental operating conditions.

A command that satisfies completely an automatic control system may, however, not necessarily be sufficient for the human pilot. The autopilot does, in general, not take care of the situation, and would for example - without any fears - precisely follow a false command into a crash.

Most human pilots on the other hand n e e d to know the situation in order to be confident. But from the command they cannot derive an overall view, because the conventional command information is not "transparent".

It is stated in two of the latest AGARD-Reports of a joint working group concerned with V/STOL Displays:

"... the pilots expressed a lack of confidence in directors alone ..." [4, p. 4].

" ... the pure flight director that has to be nulled can be flown very accurately. Unfortunately without the inclusion of situation information the pilot is extremely uncomfortable, since he is unaware of how close he is to disaster. In addition, instruments which can fail to a zero position - like the conventional abstract needle instruments (remark of the author) - *are particularly dangerous ..."* [5, p. 8] or:

" ... the lack of situation information may lead to a condition in which the command display shows all commands satisfied - while the aircraft actually flies in ... a dangerous situation which cannot be detected ..." [5, p. 6].

Since these statements on V/STOL are related to general display problems and not to aircraft characteristics they should be applicable to CTOL, too.

Due to these problems, we have all historical stages of display evolution in the modern cockpit: An accumulation of primary command and situation indications (in the ADI/HSI-Instruments) and a number of non-integratible, or redundant, 'standby'-instruments for emergency control and confidence-crosscheck, respectively. *)

However, this introduced again the dynamically unfavourable scanning:

" ... in (tests) with the pilot instructed to share his attention between directors and situation displays, the accuracy was only half as good as when the flight director received full attention" [4, p. 4].

In addition, these disadvantages in guidance precision are accompanied by a fundamental lack of spontaneous confidence caused by the high degree of abstraction of the conventional situation instruments, not only of the 'non-transparent' command information.

Among others, a statement of ANAST [7] may describe the problem:

"We are all aware that a flight director does not meet the overall needs of a psychologically satisfying display. ... The pictorial s i t u a t i o n display ... is a firm requirement before automatic landings will be considered completely acceptable".

This and other similar remarks mean a realistic outside world equivalent and not the reduced "pictorial" presentations used in today's head down instruments, the Horizontal Situation Indicators (HSI) for example.

*) The research groups of STI, for instance, have studied the problems of this operational modern display and have created many ideas which seem useful for extended application [e.g. 6].

[illegible] that recent display concepts try to solve the problem by superimposing "precision control symbols" like scales, digits, needles on the [illegible] or artificial - according to ANAST: *"psychologically needed"* - image of the outside world, head up or head down, respectively.

But even this solution which can - without doubt - introduce a further remarkable improvement, compared to the visual display technique up to now, s t i l l l e a v e s something to be d e s i r e d .

There are, too, arguments to confirm this:

"Pilots like to dim the light intensity of HUD-symbols down to the minimum usable level, because - as they reported - they want to make them transparent and look through or behind them" [8, p. 18]. *)

"A superimposed display can not naturally be interpreted simultaneously with the underlying real world view. The pilot still retains an attention-switching task ..." [5, p. 11].

The final root for such statements - which all, more or less directly, criticize the superimposition principle - is expressed, for example, by the following text extract:

" ... superimposition will not promote combination and fusion (of the different information fields) unless the head up display conforms correlatively with the visual field external to the cockpit." [6, p. 97].

We can find statements which even suggest that support for the abstract "precision control" information is expected to come from the outside world image:

Again a free translation:

" ... the danger of 'short landings' ... and the touch down spread ... are reduced, if the runway threshold is visible (in a head down TV-monitor) ..." [8, p. 23].

Wouldn't this mean that duties of precision control are delegated to the visual contact or its' analog - which is sometimes believed to be useful for qualitative quick orientation only - and that the abstract information is considered to be insufficient even for the duties it is primarily designed for?

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*) a translation

In my opinion, at least the following four arguments can be derived from these very remarkable statements:

- the abstract symbols disturb the perception of the "psychologically needed" outside world information,
- collimation (focussed at infinity) does not provide the required true integration of the information components,
- the information content of the abstract "precision control" symbology is - intuitively - considered by the pilots to be insufficient and needs to be supported by the "information behind", by the VISUAL CONTACT,
- the citation of ANAST (p. 7) indicates, that the residual display problems are not always primarily concerned with controllability but with the pilot's CONFIDENCE - a generally agreed upon but not yet very precisely defined term.

Therefore, the natural 'visual contact' information and the phenomenon 'confidence' should attract further attention in specific chapters.

Visual Contact Information

As far as precision and ease of control is concerned, the several thousand landings per day successfully performed by the "pictorial situation display" VISUAL CONTACT are no problem for well educated pilots in good visual conditions. But after reading, or listening to, some of the papers on these matters one often has more or less the impression that it is not yet completely understood why.

An extract from german literature [8, p. 19] says in free translation:

" ... The conflict between ... superimposed information ... and the pure visual contact ... will, perhaps, be better understood when in future improved knowledge about information requirements of the pilot in visual flight is available."

The question might arise, whether any reasonable valuations of contact analog displays and decisions on preferable display progress can be tried, b e f o r e the most habitual, obviously very important, visual contact information is - at least believed to be - completely understood.

Thus, intensive effort with high priority seems to be necessary to fill this gap of basic knowledge.

One reason for the difficulty in evaluating the quality of the visual contact information is probably the apparent contradiction between the obviously high success rate and the ease of control on one hand and the wide scatter of visual approach paths which seems to uncover lack of precision qualities on the other.

However, this lack of precision can, under certain circumstances, be misunderstood as lack of display quality; while in truth it expresses highly desirable "flexibility".

Precision in terms of any deviation measures of the time functions of a set of relevant variables can be a valuation criterion only if the respective variables are definitely indicated, and it is requested of and accepted by the pilot that he should closely track them.

In fact, there is no definite indication of a glide path.

In addition, a landing aircraft actually only needs to meet certain touchdown requirements, no matter, which approach path it flies along, provided it always proceeds reliably safe and according to the intentions of the pilot.

Straight or otherwise prescribed approaches are in many cases basically neither a necessity nor desirable, but an excuse for poor dynamic stability, i.e. poor guidance and display systems which do not allow VMC-like flexibility. In best visual contact, that is: where best transparency of the atmosphere and optimum habitual texture of the outside world features are available, reliably safe visual contact landings can be performed with enormous flexibility - and without relevant height perception difficulties.

Remarks on Quantification

The aversion to the "difficult-to-analyse" visual contact information is sometimes based upon the argument that height perception in terms of estimated meters or feet - whichever quantification units are preferred - is inaccurate. It is indeed; but in landings under optimum visual contact conditions, it doesn't mean very much in terms of the relevant quality measures "landing-success" and 'safety'.

Accurate perception of height, for example, is necessary only - and then the visual contact information really needs supplementation - if safe vertical distance to the not reliably visible fixed or moving environment (obscured mountains, obstacles and other traffic) must be maintained.

But this does not necessarily require abstract quantitative information elements like scales, digits and needles, nor are these very advantageous. Although, with good reasons, one units system was selected by a majority from the many possibilities to be applied in aeronautics, some pilots who don't use these units in everyday-life have to apply some extra effort to translate them into their most habitual units in order to be really informed.

Quantification by the generally usable measures: meters, feet, degrees etc., is sometimes overemphasized by far in aircraft guidance displays; perhaps because it is not understood or accepted everywhere that other directly task-oriented pictorial units can be used to give the environment meaningful dimensions. The oddity of the situation is demonstrated, if we try to imagine, for instance, that the car driver's information - the field of view in front of his vehicle - were painted with meter or feet scales and digital data for improvement of position and heading information.
Probably, this would not result in an improvement.

Problems of interpretation of transfer between different units systems do not exist at all if natural outside world units are used - necessarily in pictorial form - which are and should be very habitual to all human beings. This would give the best guarantee that orientation is immediate and reliable.

Orientation

It is generally accepted that the most familiar visual contact information is intuitively and immediately understood, in other words: there is a spontaneous orientation.

Is this really true to the full extent or are there any restrictions and if so, where precisely?

If a well-textured level plane - of the earth's surface - is seen from an altitude which is very small compared with the diameter of the globe, and the horizon lies within the field of view, we can say that attitude orientation - i.e. pitch (θ) and roll (ϕ) - is immediately achieved.

However, the orientation in azimut, and much more in the translational degrees of freedom, very much depends on the individual texture of, and on the height above, the earth's surface. High altitude gives wide-scaled "undistorted" impressions of the environment below This view is very useful for raw orientation in terms of relative distances and directions between individual locations - if these are clearly identified.

The unaided natural texture must be very familiar to the man if a fairly spontaneous orientation is to be effected. In most cases of pure VMC aircraft operation, some time-consuming observation and comparison with maps are required before the pilot is completely oriented. Therefore, well defined artificial navigational symbols will enhance quick orientation, preferably in the form of the new electronic map displays.

Simple perspective line or checkerboard patterns representing the surface do not offer any plan position information, rather only qualitative impressions of motion and height. Nevertheless, some support for attitude perception relative to the horizontal may be expected.

In addition, spatial orientation must include orientation in relation to the "moving environment" which is particularly problematic in VMC operation [21, p. 80].

We would assume high foveal sensitivity and continuous attention abilities of the pilot's visual system over the whole spheric field of view if we expect this part of the orientation problem to already be satisfactorily solved by painting aircraft tails and wingtips with bright orange colour and by installation of strobe lights.

Plan position map displays do not provide integrated vertical position information which is necessary for complete spontaneous orientation as well as for control. On the other hand, a profile view would be incomplete and therefore not sufficient as well but now in the lateral axis. Besides, the latter cannot be available in the natural visual contact for a pilot since it is, in principle, an "outside-in" display.

Immediate spontaneous attitude and position orientation is very important, as far as it's influences in manual control as well as monitoring are considered. Based on the findings of the first chapter, we must assume that full integration of all 6 degrees of freedom is required.

The unaided ' f o r w a r d ' visual contact clearly offers simple sensitive integrated directional information - simple, because the image of the environment, whatever it momentarily contains, is simply shifted transversally in the field of view. Together with the attitude angles the position is also offered fully integrated. However, in many cases it suffers from lack of typical texture. This problem is amplified by perspective distortion and by the low sensitivity and it's very nonlinear change due to motion.

Height perception for touch down is completely left to intuitive judgment.

Thus, precise visual contact approaches and landings are not as easy to learn d teach, as skilled pilots make believe; and even in best atmospheric transparency, the pure visual contact information can be dangerously misinterpreted. During night approaches, lack of foreground texture and sloping runways can cause early catastrophic ground contact [9, 10, 11]. Therefore the different attempts in simulating the pure visual contact for aircraft control have not been very successful [8, p.22].

All these shortcomings of orientation by the natural visual contact in it's different modifications require a prescribed flight path to be visible. Such a path would be desirable for economy because it can show the shortest/fastest connection between departure and destination. It is necessary for safety because it provides safe trajectories which reliably avoid dangerous interference (collision) with the environment. A prescribed path can only be made by imaginary means, since - in opposition to the hard earth's surface - space, in general, can not practically contain a real prescribed path for an aircraft. (The condensation trail of a preceding liner on an airway may be considered as an exception.)

Such a path can and should offer the most suitable sensitivity, preferably constant during each typical phase of flight, in order to enable sufficient precision. In the central perspective forward view presentation, for instance, of a street - which is the most familiar form of a prescribed path on the earth's surface - deviation sensitivity changes with the distance between the observer and the street surface. The more sensitivity desired, the more closely parallel should be the imaginary street to the prescribed path of the pilot's eyes.

With a sufficiently realistic image of a prescribed path of such a type, in addition to the pictorial attitude information, any human pilot will be completely oriented, probably as spontaneously as at all possible.

In addition, symbols similar to a street offer a tolerance limits indication for path deviations by their natural pictorial quantification.

Disorientation

Recent expert statements say the following:

"The ... displays ... have not eliminated disorientation. ... Disorientation in flight is not only a current problem; it promises to be a continuing problem... I do not think that instruments, no matter how good, will ever completely prevent disorientation." [12, pp. 5, 7].

Indeed, the present modern instruments - although some are beautifully painted in order to stimulate convincing impressions - do not prevent that even very skilled pilots sometimes have illusions which, per definition, do not correlate with the true attitude and/or position orientation and the motion within the airspace.

The drift of the human inertial orientation system requires this system to be updated by the visual orientation. If the visual inputs for the perception of the vertical - for instance from the artifical horizon - are poor in comparison to dominating cockpit references, or if vague external cues excite misleading impressions, orientation conflicts known as 'vertigo' occur.

Under certain circumstances strong illusions can happen even in excellent visibility in flight. This is possible, for instance, on high altitude flight above flat untextured haze layers with some reference marks (cumulonimbus) at the horizon.

In turns under such conditions the horizon texture sometimes seems to move and the aircraft appears to be the fixed reference. Some pilots even can intentionally produce the illusion of fast lateral or even backward translational motion! *) Psychological background to such experiences is explained in a book of BEATY [21].

*) observations of the author

Such experiences should not be treated as an illness of the pilot but as naturally explainable reactions of the human (visual) orientation system to the sometimes ambiguous visual contact information:

The absence of distributed near-by texture - which is necessary in order to sense changes of position - allows the eye and brain to interpret the far-away azimutal turn motion as a fast unnatural translational motion of the aircraft.

There will be no doubt that the orientational disturbances are definitely avoidable if the presentation of the environment contains sufficient elements of vertical and/or horizontal orientation which are about as urgent and sensitive as in everyday visual contact of human beings.

The presentation of the prescribed path which, in the previous chapter, was found to be necessary, could be designed so as to reinforce to a convincing degree the impression of a vertically and horizontally oriented fixed outside world reference.

It seems to be realistic that a display with such characteristics has a good chance of completely eliminating disorientation. But strictly speaking, confirmation is still left for experimental research in real flight.

Confidence

The dominating significance of the display quality 'confidence' was mentioned in some earlier papers [e.g. 1], and confirmed in one of the cited AGARD-Reports:

"Pilot's confidence is probably the most important single factor in achieving operational all-weather landing." [5, p. 3]

Obviously, there are different contributions to the phenomenon 'Confidence':

- speed and reliability of orientation,
- ease and precision of control,
- flexibility of flight path selection,
- the - display dependent - proficiency of the pilot
- and the functional reliability of the electronics

All these more or less remarkably influence the pilot's confidence in the overall system and situation.

Build-up of confidence in some new All Weather Systems is almost exclusively based on the - without doubt very important - last component. But in my opinion, confidence produced only by extremely reliable equipment, is very expensively purchased because very much of the unactivated human abilities have to be substituted. There is no question that pilots will fly such systems because they have no choice [1, 13]. According to their human tendency to adapt to almost everything, they will develop a substitute for confidence which is sometimes said to be a psychological progress [11, p.966], but should be better called fatalism.

The following general remark applies to confidence as well as to the orientation problems:

The pictorial display should have a high degree of realism, a highly sensitive perspective which always seems to be a true undistorted, although possibly simplified, visual contact. There appears to exist a threshold in realism resulting in a respective discontinuity in human acceptance. As soon as sufficient realism is offered, human imagination automatically completes the "picture of the situation" and unequivocally integrates it with the inputs of the other orientation sensors. If this threshold is not reached, however, imagination is not exited and the pseudo-pictorial presentation is felt to be not much more than a specific arrangement of symbols. The psychologically rooted components of confidence don't seem to be activated by displays with too limited realism.

Therefore, too, permutation of abstract symbols, colors and other means for information coding, does not seem to be a very effective tool for achieving desirable progress in display research and technique.

In my opinion, here are also some chances *for further efficient* research.

Problems of monitoring, decision making and manual take-over

Some papers could make one believe that the man/vehicle-cooperation problem could be characterized with headlines such as:

- "reduce the workload of the man in the cockpit",
- "the pilot's task should be kept as simple as possible" [5, p. 2]
- "the pilot must progress from being the operator to becoming the manager" [15].

That the root of the problem would be missed by such a progress seems to be indicated by the following translated remarks:

" ... It is the question, how far man may be supported by complex subsystems, without causing hazards for the whole in case of any failure. Too much "foolproof" systems wouldn't maintain the pilot sufficiently trained ..." [16]

"The step from ... an extremely easy monitor task ... to the more complex ... (one which requires mental) ... measurement and interpretation of information (as well as) manual control must remain acceptably small." [17]

Of course, the step from extremely easy monitoring to the m o s t complex basic form of a manual control task requires a jump over the maximum possible difference of difficulty levels!

Therefore, it can only be m u c h too demanding, particularly because it would have to be mastered in very rare and unexpected cases and because even the already continuously trained manual task is too difficult - as far as instrument landings in critical cases are considered!

If the statements above are true, this conclusion seems to be permitted:

A reasonable monitoring task

- includes fully competent manual take-over by the pilot, and this
- requires the best possible information display, which must be by far much more capable than the 'state of the art'.

The tendency to confront pilots with a more or less arbitrary collection of different command, situation and monitoring instruments or electronic drawings and, being discontent with his necessarily inconsistent resulting performance, to push him into the pseudo-active role of a monitor and "go automatic or overshoot"-decisionmaker will hardly lead to optimum solutions.

It is unrealistic to derive human dynamic skills from observations of conventional instrument flight. Since the extremely wide step mentioned above is well within human pilot's capabilities as soon as he flies in good visual conditions, the assumption is justified that a display which could offer information really equivalent to visual contact and including the necessary and desirable improvements would allow him to perform at least as well.

However, manual take-over needs manual skill, necessarily based on training, which will be more and more reduced by automatic operation. Since man usually applies no more than the effort which is requested from him, the manual skill is not developed within human limits to the desirable degree by the information principles used today.

Insofar, it is doubtful that the pilots' task should be made "as easy as possible". Manual skills should be kept high by a reasonably demanding task presented by respective display qualities.

Resulting Remarks on Basic Suitability of Contact Analog Displays due to Human Characteristics

Referring to the shortcomings of the visual contact there are numerous comments in literature which condemn this natural information source as a model for display development.

The well known fact that the use of the visual contact in flight is not so easy to teach and to learn as it seems to be when observing experienced pilots is basically caused by the deteriorations of information content as soon as the pilots' eyes are raised high above the surface.

But this does not necessarily postulate the so caused deficiencies of the visual contact to the ground to be unavoidably associated with the other, the doubtless superb qualities of this natural display. The possibilities of today's artificial electronic image generation would allow an interruption if such an undesirable compromising connection would exist. In other words, it cannot be prohibited in using, extending and amplifying the favourable pictorial elements and in deleting the superfluous or even unfavourable ones.

Abstraction of information, as well as destroying it's natural integration by a break down into single parameters, and a mixture of different display principles should be abandoned because much or all of the unique qualities of the environment view model are lost. It can be abandoned because all the necessary information - in quantity and quality - can be presented in a pure pictorial form.

An interesting remark, received in a discussion, and it's analysis will probably further contribute to clear the "difficult-to-measure" problems:

"A very habitual information, like the perspective outside world view, is not necessarily an optimum."

To me, this appears to be very true even in general and neither restricted to one type of information only, nor to vehicle control alone.

The appearance of the environment as picked up not only by the visual system but also by other closely correlated sensory modalities obviously reaches an absolute "familiarity maximum" for almost every individual during his evolution from childhood. Beyond this it is highly probable that, due to the "principle of amplifying selection" in the evolution of mankind, human sensors should have adapted to the appearance of the environment. This particularly because the appearance and it's change in human motion remained the same during the very long time of the evolution process.

Probably therefore, the eyes in their normal 'zero' attitude, looking in the direction of motion, became very able to sense shifts of the path-stabilizing attitude angles due to foveal sensitivity and/or due to very precise eye tracking ability. This is supported by peripheral view which, in addition, became very sensitive to streamer vectors and asymmetries indicating transversal deviations.

This should be one strong, although not the only, argument for the visual contact on earth's surface being preferable in comparison to other more or less artificial information principles.

Other - to engineers probably more convincing - arguments should come from considerations dealing with the suitability of the information content under control dynamics aspects. These matters are discussed in the next chapters.

Due to the finding that weaknesses of poor information (display) qualities are principally the roots of the problems, human pilots should not be treated as underdeveloped subjects as far as the task of stabilization and control of dynamic systems is concerned. This became almost common habit in argumentations which claim for superiority of automatic control systems. It should be surprising that in such cases it is not tried to explain the discrepancies between this attitude on one hand and the admirable precision of the well known close formation flight acrobatics controlled by a "purely pictorial" visual contact information on the other. The argument that those are performed by rare exceptionally talented individuals does not fit. Very many, if not all of the thousands of fighter pilots for instance, were, are or will be able to reach similar skills because they are all human controllers "designed" and selected, educated and trained by the same principles.

However, then it must also be accepted that some remarkable "rest" of dynamic adaptation is left to learn for many very experienced pilots who primarily have to manage instead of flying their aircraft.

Without doubt it is conceded that the 'combat ready' fighter pilots have to be fit in the precision task formation flight for normal service. Thus it won't be unreasonable to request adaptation of pilots to a similarly demanding task given by a pure pictorial display i f this display would be highly desirable from an overall standpoint.

Concluding Problem Definition

As an output from the preceding chapters, the design targets for future displays would in short be:

1. Spontaneous reliable orientation, eliminated disorientation; (realized by →): → deviation-sensitive advanced contact analog;
2. Easily controllable precision: → fully integrated c... ...ties;
3. VMC-like flexibility: → advanced contact analog;
4. Maximum and economic development of manual skill: → demanding advanced contact analog;
5. Best monitoring qualities: → deviation sensitive advanced contact analog;
6. Satisfaction of all confidence components: → results from point 1 through 5.

Thus, a 'demanding deviation-sensitive advanced contact analog display with fully integrated command qualities' would be required. Or, returning to the described limits of the 'state of the art' (p. 10), the problem to be solved could be defined by the following overlapping questions:

- How could information for spontaneous confidence a n d for precision control be combined, "integrated" command be achieved, w i t h o u t the disadvantage of superimposition of different types of information?
- Is there a type of display which offers all simultaneously?
- How could the contact analog information which obviously is necessary to amplify confidence artificially be improved in order to offer the precision control aids which are not available in the visual contact in the natural or, much less, in simulated form?

Test Results

We tried to answer at least parts of these questions in an experiment last year, where we compared simulator tests, flown with three different stages of conventional display evolution (Fig. 2) and with the Channel-Display, which was described in earlier papers [18, 1, 13]. The latter was especially developed to fulfill the design targets mentioned before.

Figure 3 shows the display arrangement which includes a relatively poor realization of the channel display due to very limited computer capacity.

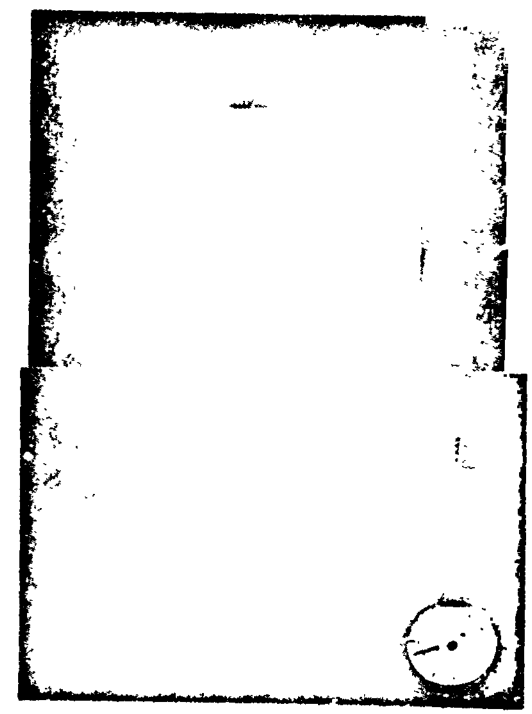
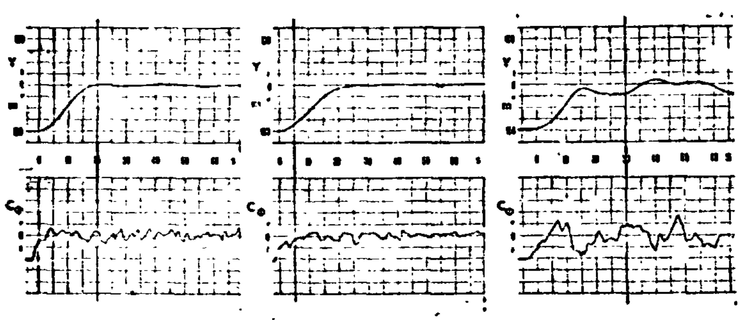


Fig. 3 Conventional Instruments and Channel Display

Fig. 4 shows graphs of the lateral offset and of the bank angle command C_ϕ for three typical test runs flown in a fixed base simulator with the Flight Director (FD), the Channel Display and the conventional ILS.



Flight Director Test controlled according to C_ϕ | Channel-Display Test C_ϕ not displayed | Basic ILS Test C_ϕ not displayed

Fig. 4: Comparison of test graphs

There are comparable flight path traces in the FD and Channel tests in the interception as well as tracking phases. It is worth being mentioned that the C_ϕ- signal reaches zero after a similar time lapse from the start of the channel-run as well as the FD-test.

The FD-test was controlled by zeroing the C_ϕ-Signal resulting in the time function of the residual alternating command error. In the channel test no command signal was of course visible for the pilot. In spite of that there is a comparable quality in the command traces, the FD showing higher frequencies only caused by the direct response of the pilot to the command needle which is deflected under the influence of gust-induced motions.

The natural or artificial visual contact is considered to be a pure situation information. Insofar, it should be surprising that the Channel-Display, which is evaluated from this model, exhibits a guidance precision and path error smoothness which is comparable to that of the FD, and much better than that of the abstract situation instruments.

Fig.5 depicts a more detailed processing of C_ϕ-traces of FD- and Channel/Tunnel-runs *) and additional traces from basic ILS, distributed as well as accumulated.

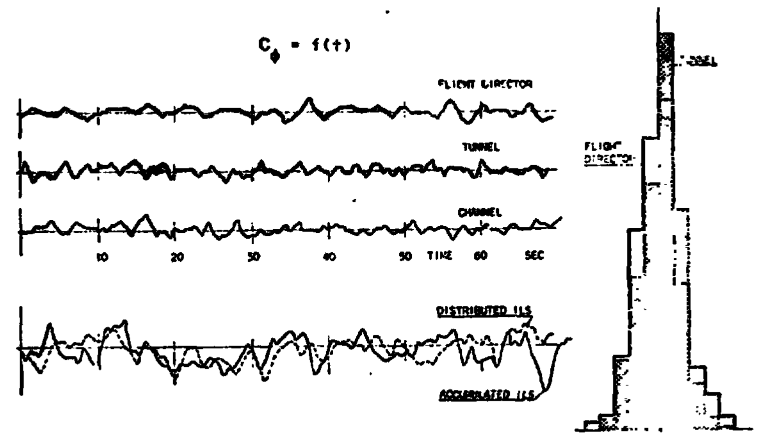


Fig.5: Comparison of evaluated C_ϕ- traces**) histograms

The histograms of C_ϕ, superimposed for comparison,***) belong to the first 2, the FD and Tunnel traces, respectively. Obviously, the results are even better with the Tunnel than with FD in this case.

Channel and Tunnel traces are similar in frequency and amplitude. The tasks with raw distributed and accumulated ILS had identical gust time functions and show much [illegible]er C_ϕ-error functions which are similar, too.

To me, such results suggest that the channel display inherently contains a sort of command characteristic comparable to that of the typical FD.

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*) Tunnel = a closed channel (see Fig. 6)

**) These traces were taken from another type of analog record than those of Fig. 4. With regard to this, it will be recognized that the dominating frequency of the traces of the FD tests is the same in Figs. 4 and 5.

***) Of course, single test graphs do not seem to be very convincing. But a very laborious manual processing had to be done because the magnetic tapes became unusable after a fire in our simulator rooms. However, the analog records selected are typical.

And, indeed, we find the analog of the FD-equation in the perspective picture of a Tunnel. (Fig. 6)

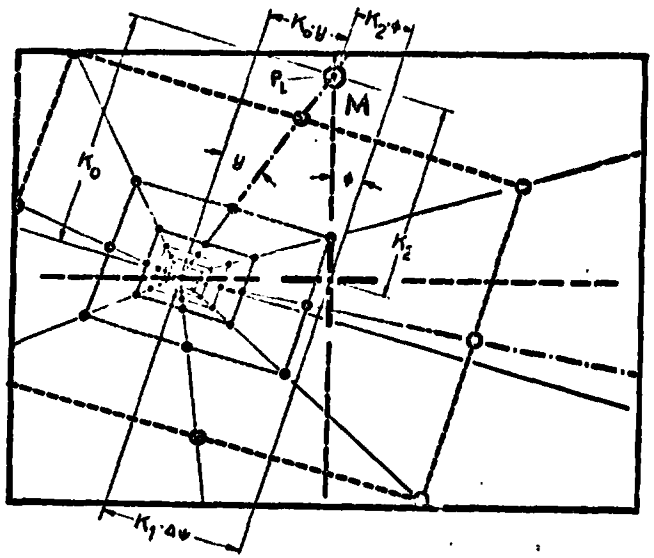


Fig. 6: The Director in the Tunnel Display

The lateral deviation is transformed into an angle y due to the laws of central perspective projection, while the heading difference ψ is represented by a lateral offset of the tunnel's vanishing point from the reticle. The bank angle ϕ is of course given by a corresponding rotation. Finally, the view angle magnification ratio defines the coefficients K_0, K_1 and K_2, so that the simplified FD-equations can be derived from Fig. 6:

$$C_\phi = K_0 \cdot y + K_1 \cdot \Delta\psi + K_2 \cdot \phi = 0$$

The equation $C_\phi = 0$ is satisfied as soon as a point M at the upper end of the reticle coincides with another point P_L on the upper centerline of the Tunnel.

Of course, this does not mean that pilots will focus their attention on these two markings and closely track them. Instead they probably learn in a modified type of 'Successive Organization of Perception' [6] to perceive the correct progress peripherally and to apply the "command characteristic" intuitively in a favorable flexible manner.

There was a remarkable difference in the control strategies of the Channel/Tunnel tests and the FD-runs. The Channel/Tunnel display enables the pilot in discriminating between bank, yaw and displacing disturbances and in reacting individually with the respective control. Control inputs were applied well coordinated or independently, whichever was preferable [18]. With the "nontransparent" FD the pilot has no choice but to react with the aileron only although, in case of a ψ-disturbance, the most reasonable direct action would be with the rudder.

Since the stability of a command control system depends on the magnitudes of the coefficients and since the coefficient K_0 is a function of the cross-section size of the channel, it is desirable to know which channel calibration would be optimum with respect to precision and ease of control.

Fig. 7 is a qualitative diagram of the relations between the channel size and the tracking accuracy.

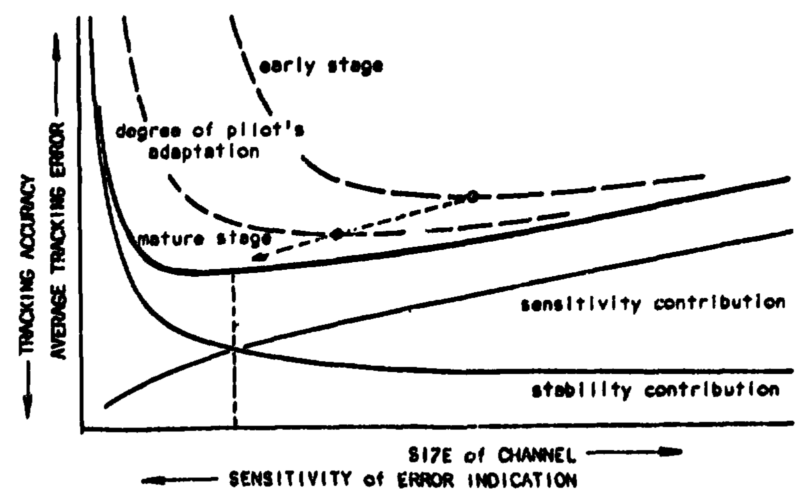


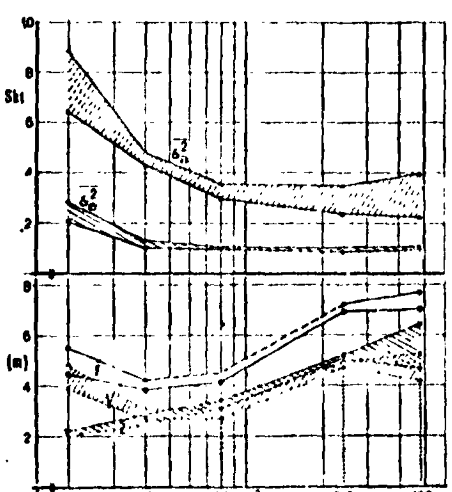
Fig. 7: Average tracking errors VS size of channel

In general, we can expect an increase in the tracking errors with a growing size of the channel due to the reduction of signal sensitivity. On the other hand, there will be a hyperbolic contribution because the closed loop dynamic stability will progressively decrease if the channel is tightened; and thus deviation sensitivity (or K_0) grows beyond favourable values and causes increasing oscillatory overshoots.

The sum of both will necessarily have an optimum at a certain channel size. Further the optimum will be a function of other parameters like vehicle dynamics, type and level of the disturbances, and degree of adaptation of the pilot. Since the stability contribution will be more influenced by the pilot's skill level than the sensitivity contribution, the optimum will drift towards smaller size during the adaptation process.

The position of the optimum is particularly important, because the channel shall additionally provide inherent motion tolerance information where necessary; for instance, during the final phase of the landing. This will help to avoid superfluous precision and control activity, and will allow more flexibility, all being factors which contribute to confidence.

In a series of test runs with one pilot at an approximately constant level of adaptation the influence of channel size was investigated (Fig. 8).



CONTROL ACTIVITY

$\bar{\delta}_i^2 = \frac{1}{T}\int |\delta_i^2|\, dt$

i = e → elevator
= a → aileron

TIME AVERAGE ABSOLUTE ERRORS

$\bar{y} = \frac{1}{T}\int |y|\, dt$ $\qquad \bar{r} = \sqrt{\bar{y}^2 + \bar{z}^2}$

$\bar{z} = \frac{1}{T}\int |z|\, dt$

Fig. 8: Tracking Error and Control Activity as a Function of Channel Size

The time average absolute errors in the lateral (y) and vertical (z) direction as well as their vector sum r and the respective control activities are drawn as functions of the channel width B at a constant ratio H/B = 3/8.
The results reproduce the functions as they were expected according to Fig. 7.

The spread of values was not, or not only, caused by stochastic influences. With one exception, the upper limit represents the early, the lower limit the later tests. Apparently, there was still an adaptation process going on.

It seems to be important to mention here that statistical evaluation of such tests with many subjects would hardly exhibit these very important results. They would probably be masked by undetermined influences like different unknown adaptation levels of the subjects. With other words, such and other traditional "laboratory rituals" [5, p.12] should be applied with caution. Otherwise, misleading conclusions could be encouraged.

While there is a minimum of $\bar{y}$ (Fig. 8) at 40 < B < 80, $\bar{z}$ continues to drop with decreasing B. This difference was obviously caused by the lower difficulty level of the control task in the vertical axis in comparison to the lateral. This results partly from the higher order of the lateral task, partly from the difference in χ-sensitivity (B/2 > H; Fig. 9).

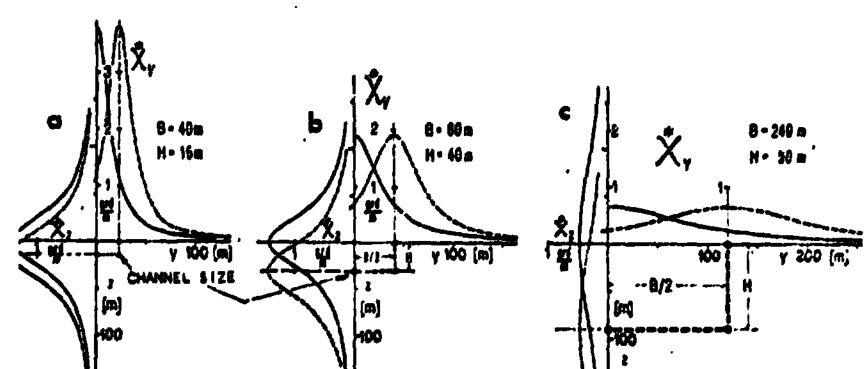


Fig. 9: Three examples of vertical (χ_z) and lateral (χ_y) deviation sensitivity as functions of the resp. deviations .(Derived in [20]).

The control difficulty differences are recognizable (Fig. 8) from the control activity functions, as well. The δ_a^2-activity has a wider "scatter" - i.e. the pilot still continued to adapt - and starts to increase at a larger B. Especially the consistency of the elevator activity is believed to be an indication of the reliabilty of the results.

The differences in control activity partly originated from the different control sensitivities and partly from the extraordinarily poor lateral control characteristics of the simulator.

The most important overall result, however, appears to be that the minimum of the resultant average error $\bar{r}$ lies at a channel width B which approximately coincides with the width of a typical runway!

Thus, for the conditions selected, we had coincidence of the optima of three of the most important display characteristics: Ease (1) and presision (2) of control and tolerance information (3).

A further interesting observation during the tests confirmed by the results was that the stability of the closed-loop system, including a well adapted pilot and the Channel/Tunnel display, was much less dependent on "variation of coefficients" than a flight director controlled system in principle is.

BEYER et al. [19] have shown that the coefficients can be selected to effect either a high precision control aid with an oversensitive, "high workload" indicator or a less demanding, less precise control task. They stated that, therefore, "no really optimum selection of the coefficients is possible" [19, pp. 20, 21].

A performance restricting compromise is needed. Although this paper deals with the "quickened display" *) for a heading control task, and not for the more critical flight path control which is the relevant type of operation today, the problem would principally correspond with the findings derived from the simpler system in [19].

With the conventional "nontransparent" FD any human pilot is necessarily condemned to operate as a poor constant amplifier. When using the inherent command characteristic of the Channel/Tunnel display, he is able to develop and apply his intelligence-based high adaptability. He can thereby compensate the changes of system dynamics caused, for instance, by variations of display and control sensitivities or of aircraft characteristics.
In Fig. 8 the increasing control activity, with decreasing error, indicates the compensating ability of the human pilot.

*) in this respect the "quickened display" may be considered to be the same as the flight director

There are still some questions concerning, for instance, the computer sophistication for realizing the Channel Display, it's information content in cases of large deviation, the suitability of the available guidance systems for feeding the display and it's failure warning and survival abilities. These points are very important from the operational standpoint and their evaluation depends very much on less provisionary realization and flight testing.
Although there are many favourable arguments which already seem to be convincing, these should now be retained until they can be reliably confirmed.

Conclusions

1. As long as pilots are able to fly and land an aircraft manually in good visual conditions, and there is any deterioration in performance as soon as the visual conditions get worse, the root of the problem is a poor display.

2. It is recognized that man must scan when provided with a number of single information sources. Thus, he can unfavourably use small asynchronous sections of the continuous information flows only. Therefore, it is necessary to derive that scanning should definitely be avoided for the dynamically demanding task of attitude and flight path stabilization.

3. Although local condensation and superimposition of different information allow some improvement, these methods do not completely eliminate the need for some undesirable "attention switching".

4. A dynamically complete and correct pure single command indicator would allow the removal of scanning, but it is not "transparent" for orientation which the human pilot needs for confidence. Observing the command needle, for instance zeroed by the autopilot, does not sufficiently satisfy this need.

5. Neither additional abstract basic conventional data nor the pseudo-pictorial situation displays, especially such in the plan position or profile view, provide sufficient confidence in critical cases. In addition, they distract attention from the primary control information, which distraction conflicts with the item 2.

6. It is necessary to fully understand the visual contact information before successful comparing valuations of present display principles and reliable decisions for desirable future development can be made.

7. Selfexplanatory, complete visual contact to habitual environment fully satisfies the human need for confidence. But in most cases the visual contact in flight, even in good visual conditions, does not contain sufficiently sensitive three dimensional position information, especially in the vertical.

8. The deficiencies can be overcompensated, the superb qualities amplified, by the presentation of a - necessarily imaginary - prescribed flight path. This should be calibrated in intuitively obvious pictorial elements of preferably horizontal and vertical orientation which provide sensitive vertical, lateral and longitudinal position information. A prescribed path eliminates ambiguity and attention-demanding mental processing.

9. Especially for the use of precision control (item 2.) and complete immediate orientation, this prescribed path can only be presented in fully integrated form, together with the three rotational degrees of freedom, by central perspective projection of the 'forward' view. Only this single format emphasizes the information components approximately according to their importence. An additional "inside-out" map display is desirable for raw orientation.

10. The Channel/Tunnel-Display is designed according to the findings 1. to 9.

11. Furthermore it has been shown by test results that this display contains inherent command characteristics which - in contrast to the conventional "nontransparent" flight director - leaves situation information available and thus can be used in an extremely flexible manner.

12. The pictorial integration used in the channel display allows an increase of the sensitivity of deviation information beyond that which is acceptable in "abstract integration" (deviation coefficient in the command equation) in order to maintain dynamic stability.

13. The acceptance for high deviation sensitivity allows the use of channel dimensions as meaningful tolerance limit indications even in the - generally most critical - landing phase. It was shown by test results that optimum tracking precision can be achieved with a channel calibrated for standard runway width.

14. Thus, an objective measure is possibly achieved for the momentary performance level of a pilot, for the dynamic aptitude of student pilot candidates or for sufficient runway width.

15. Although it does not agree with the philosophy of offering a display which is "as easy to control as possible", two pilots expressed that they felt relaxed when changing over from modern conventional instruments in simulator tests. Director tracking appeared to be a comparatively stultifying primitive task.

16. In any case there was no problem of manual take over from a failing autopilot in simulator tests with the channel display. The channel, which simultaneously allows quick orientation and manual precision control, was felt to be optimum for the monitoring and decision task, too. In general, monitoring and manual control should be most convenient with one and the same display.

17. With the Channel/Tunnel-Display spontaneous orientation and VMC-like flexibility will be achieved, disorientation problems - very probably - completely eliminated.

18. Regard for different display quality requirements does not necessarily require a compromise in the strict sense which includes reductions in the performance of the conflicting components. There are combinations - additive and superimposed displays, for instance - which suffer from such reductions. Other combinations, the channel display for example, can offer qualities which are more than the sum of the components.

19. The problem of safely overcoming the extraordinary demands for dynamic capability in case of a necessary unexpected take-over under adverse conditions cannot be solved by separation of the pilot from these basic demands. Instead of artificially "making his task as easy as possible" only - with the attitude stabilization (which is very useful), higher sophisticated flight directors etc. - the reserves of human dynamic adaptability should be activated by better displays in order to achieve an efficient and economic increase of safety.

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